Bottomonium melting at temperature well above Tc

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Abstract

We fit the lattice QCD data of Kaczmarek et al for the free energy F1 and internal energy U1 with a class of Coulomb, constant and linear potentials, both pure and screened, matching the large distance to the short distance parts of the lattice QCD finite temperature energies. We also include the hyperfine potential in F1 and U1. We detail the bottomonium (and charmonium) binding and the melting temperatures, both for the groundstate and for the excited states, relevant for Hard Probes in Heavy Ion Collisions at LHC, where temperatures well above Tc will be reached, much higher than the temperatures reached in previous Heavy Ion Collisions.

Bottomonium and charmonium are good prototypes to study finite T quark-antiquark potentials [1] since

$$m_b, m_c >> \Lambda_{QCD}, Tc \tag{1}$$

allow us to neglect spontaneous chiral symmetry breaking, relativistic effects, coupled channels, and temperature in the quark propagators. In this short contribution we simply aim, in the spirit of [2], to solve the Schrödinger equation with static lattice QCD potentials.

The string confinement model is dominant at moderate distances while at short distances the attraction is a Coulomb. Olaf Kakzmarec *et al.* [3, 4] fitted the lattice QCD static potential, for spinless or infinitely heavy quarks,

$$V(r) \to \frac{-4\alpha}{3\,r} + \sigma\, r \tag{2}$$

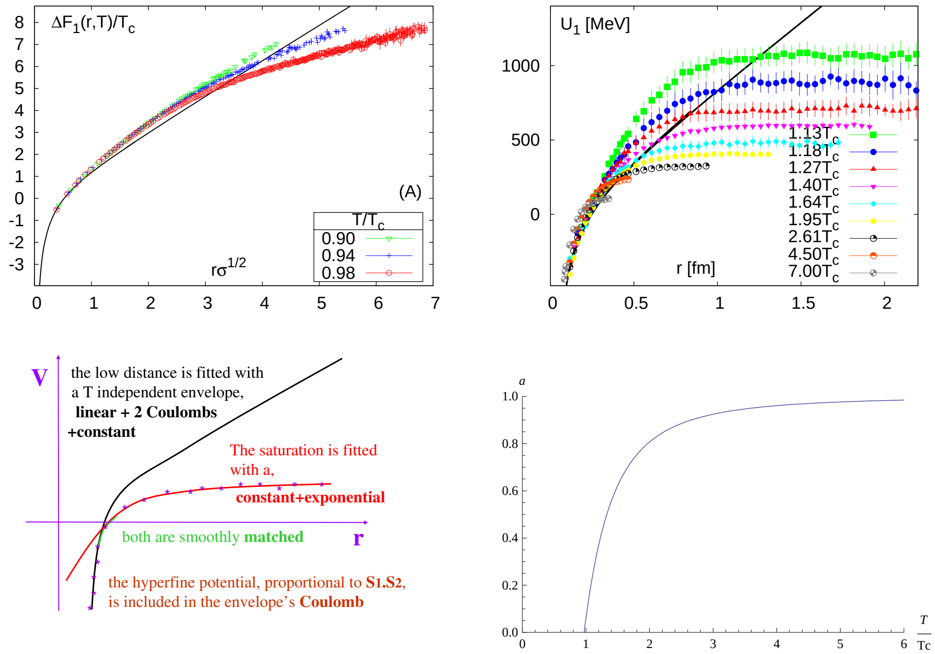

Figure 1: (a) Free Energy F_1, (b)Internal energy U_1 both computed in Lattice QCD by Kakzmarek *et al*, (c) the fitting method, and (d) the mixing energy parameter $a(T)$.

with $\alpha = 0.212$ all in units of $\sqrt{\sigma} = 420MeV$. Including spin, at low distances the perturbative One-Gluon-Exchange OGE produces a hyperfine splitting. As a first correction due to our heavy but not infinite quark masses, we add the hyperfine $\mathbf{S}_1 \cdot \mathbf{S}_2$ term that we fit to the $J/\psi - \eta_c$ mass splitting and to the $\upsilon - \eta_b$ mass splitting (where we use the very recent Babar result [5] of $M_{\eta_b} = 9388.9$ MeV/c^2),

$$V(r) = \frac{-4\alpha\,(1 + f\mathbf{S}_1 \cdot \mathbf{S}_2)}{3r} + V_0 + \sigma\, r \tag{3}$$

where $f_c = 0.33$ and $f_b = 0.12$.

At finite T, we use as thermodynamic potentials, the free energy F_1 and the internal energy U_1, computed in Lattice QCD with the Polyakov loop [3, 4]. They are related to the static potential $V(r) = -fdr$ with $F1(r) = -fdr - SdT$ adequate for isothermic transformations and with $U1(r) = -fdr + TdS$ adequate for adiabatic transformations. The potentials are fitted [6] as described in Fig. 1. We follow Cheuk-Yin Wong [2], who used the local gluon pressure to combine the free energy F_1 and the Internal

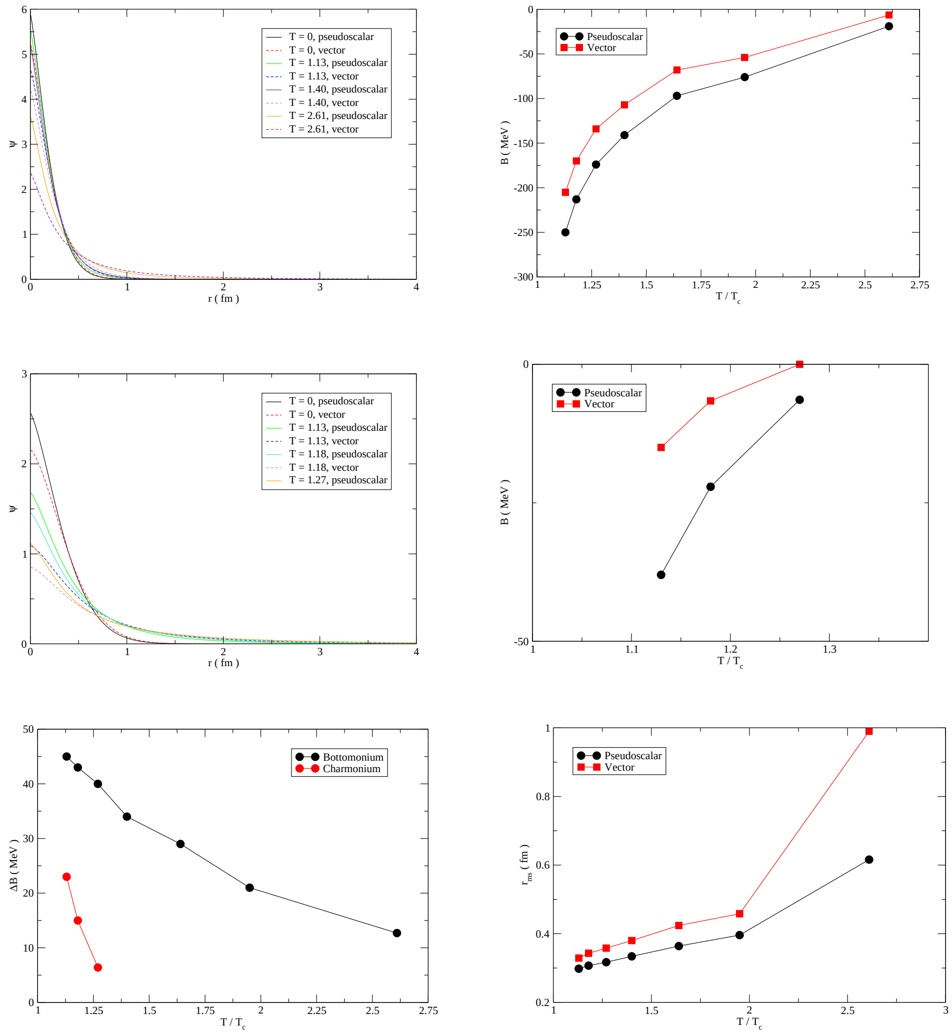

Figure 2: (a) bottomonium Υ and η_b wavefunctions, (b) bottomonium Υ and η_b binding energies, (c) charmonium $J\psi$ and η_c wavefunctions and right, (d) charmonium $J\psi$ and η_c binding energies, (e) bottonomium and charmonium hyperfine splitting $M_{vector} - M_{pseudoscalar}$ and (f) bottomonium υ and η_b radius mean square.

energy U_1 with the function $a(T)$ also depicted in Fig. 1,

$$V_T(r) = \frac{3}{3+a(T)} F1(r,T) + \frac{a(T)}{3+a(T)} U1(r,T) \ . \qquad (4)$$

Solving the boundstate equation [6] for the potential $V_T(r)$ defined in eq. (4), we find the results show in Table 1 and in Fig. 1.

T/Tc	B_0	B_{PS}	B_V	Δ
1.13	-213	-250	-205	45
1.18	-178	-213	-170	43
1.27	-141	-174	-134	40
1.40	-112	-141	-107	34
1.64	-72	-97	-68	29
1.95	-58	-76	-54	21
2.61	-7.8	-19	-6.4	12.7

Table 1: Table of the Bottonomium binding, B_0 is the binding energy without hyperfine potential, B_{PS} is the binding energy for the Pseudoscalar, B_V is the binding energy for the Vector, and $\Delta = B_V - B_{PS}$ is the hyperfine splitting.

To conclude, we find that in $I = 0$ quarkonium, the only existing boundstates above T_c are the $L = 0$ heavy quark groundstates with spin 1 and spin 0. The hyperfine potential splits the melting temperatures of the spin $S = J = 1$ vector and the spin $S = J = 0$ pseudoscalar. Bottomonium melts at higher temperatures, at $T = 2.7\,T_c$ for Υ and $T = 2.9\,T_c$ for η_c, relevant for the LHC. Charmonium melts close to $T = T_c$, at $T = 1.2\,T_c$ for J/ψ and $T = 1.3\,T_c$ for η_b, rather cold for the LHC.

In the future, using modern quark model techniques, one might extend the present work to study light quark chiral symmetry breaking and quark mass generation, compute the spectrum of any hadron and compute the interaction of any hadron-hadron, at finite T.

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